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Late harvest and foliar fungicide acted together to minimize climate change effects on summer maize yield in the North China Plain during 1954–2015

Yuanyuan Wang[a,1], Lili Zhang[b,1], Nan Zhou[a], Lina Xu[d], Jincheng Zhu[c], Hongbin Tao[a], Shoubing Huang[a,*], Pu Wang[a,*]

[a] College of Agronomy and Biotechnology, China Agricultural University, Beijing 100193, China
[b] Dandong Academy of Agricultural Science, Liao Ning-Feng Cheng, 118109, China
[c] Hebei Academy of Agriculture and Forestry Sciences, Shijiazhuang 05000, China
[d] School of Science and Technology, Henan college of Science and Technology, Xinxiang 453003, China

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ABSTRACT

Global climate change has raised many concerns especially on the food security. It becomes increasingly important to understand the underlying mechanisms and to find out strategies to adapt climate change. Climate data from 1954 to 2015 at one representative experimental station in the North China Plain, model simulation, and a 5-year field experiment from 2011 to 2015 worked together to detect effects of climate change on maize yield and adaption methods. In the field experiment, two foliar fungicides "Cabrio" and "Opera" were sprayed at 9-leaf stage of maize to delay leaf senescence under four different plant densities (67,500, 75,000, 82,500, and 90,000 plant ha^{-1}) and two nitrogen levels (120 and 180 N kg ha^{-1}). In the past six decades, growing degree days (GDD) significantly increased at a rate of 4.4 °C yr^{-1}, solar radiation significantly decreased at a rate of 12.93 MJ m^{-2} yr^{-1}, and annual precipitation slightly decreased at the experimental site. The climate change tended to significantly reduce maize yield in the cropping system winter wheat – summer maize in the North China Plain. The reduced growing period (particularly reproductive growing period) by the warming climate could explain the reduced maize yield. Foliar fungicides greatly delayed leaf senescence especially at high plant densities and low nitrogen levels. On average, leaf area index was 2.7 vs. 1.9 between treatments of spraying fungicides and spraying water at harvest. Dry biomass was significantly increased by fungicides especially in the late growing period. Together with increased leaf productivity, 10-day delayed harvest could offset the adverse effects of climate change on maize yield in the past six decades in the North China Plain.

Varieties and crop management that can increase reproductive growing period as well as enhance leaf productivity of maize (particularly in the early grain filling period) are likely to produce more yield and adapt to the progressive climate change.

1. Introduction

An increasing body of evidence indicates that global climate change has adverse effects on crop production (Asseng et al., 2015; Lobell et al., 2011), increasing the challenge in food security with respect to the continuously growing population (Godfray et al., 2010; Foley et al., 2011). The North China Plain is one of the largest agricultural production areas in China, covering a total area of 320,000 km^2, and more than half of which is used for agricultural production. Climate change in this region was estimated to reduce yields of many crops in the past several decades (Chen et al., 2010; Wang et al., 2012; Zhang et al., 2013; Xiao et al., 2016). Warming climate is the most important contributor to the reduced yield by affecting phenological development and crop productivity (Craufurd and Wheeler, 2009; Siebert and Ewert, 2012; Tao et al., 2012). And Warming climate likely reduces yield of summer maize more severely in this region due to the heat stress at the sensitive growth stage such as silking (Edreira et al., 2011; Zhang et al., 2015a, 2015b).

To adapt the warming climate, maize cultivars with a longer growing period are supposed to offset the negative effects of climate change (Sacks and Kucharik, 2011; Liu et al., 2013; Xiao et al., 2016). As well, adjustment of sowing time (i.e. earlier or delayed sowing, depending on the regions) was also estimated to be an effective strategy (Kucharik, 2008; Zhao et al., 2015; Dobor et al., 2016), especially to

* Corresponding authors.
E-mail addresses: huangshoubing@cau.edu.cn, huangshoubing@163.com (S. Huang), wangpu@cau.edu.cn (P. Wang).
[1] These authors contributed equally to this article.

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avoid the high temperature coincidence with sensitive stage of reproductive growth (Prasad et al., 2002; Hedhly et al., 2009). However, these adaption strategies would be less effective in the double cropping system winter wheat – summer maize in the North China Plain. First, most of the modern maize cultivars cannot reach physiological maturity at normal harvest due to the short growing season allowed in the double cropping system (more or less 100 days, Sun et al., 2007). On the other hand, it is difficult to greatly advance sowing of maize, which would greatly reduce wheat yield due to the early harvest. Double-delay cropping technology (i.e. delayed harvest in maize and delayed sowing in wheat) could increase yield in both maize and wheat (Sun et al., 2007; Wang et al., 2012). But the delay in the harvest of maize is limited due to the low temperature at late growing period, which can hinder grain filling (Thakur et al., 2010). And, too late sowing would reduce wheat yield in the cropping system of winter wheat – summer maize (Sun et al., 2007).

Besides, solar radiation in the early grain filling period of summer maize is limited due to the cloudy weather in the North China Plain, restricting maize yield increase (Xu et al., 2013). With the climate change and environmental stress in mind, to further increase summer maize yield will become more difficult in this region. Increasing plant density with modern cultivars that are tolerant to high plant population is considered as the most important strategy to increase maize yield (Tokatlidis and Koutroubas, 2004; Hernández et al., 2014). The dense plant population, however, can result in ear rot and mycotoxin contamination in maize kernels (Blandino et al., 2008; Mukanga et al., 2010), and accelerate leaf senescence (Borrás et al., 2003; Antonietta et al., 2014) especially in hot and humid environment. With the fast development in agriculture, agro-ecology and sustainable agriculture raise more concerns (Bellon and Hemptinne, 2012; Velten et al., 2015). Reducing chemical fertilizer input such as nitrogen that can reduce leaf productivity, as well as maintaining high grain yield of maize will become a challenge, particularly in the North China Plain (Chen et al., 2014; Wu and Ma, 2015).

Increasing leaf productivity and delaying leaf senescence have important implications to yield increases of many crops (Greef, 1994; Bertelsen et al., 2001; Valentinuz and Tollenaar, 2004). For this, foliar fungicides have been widely used in the United States (Munkvold et al., 2008; Blandino et al., 2012) and other countries such as Canada (Hooker et al., 2008) and China (Wan et al., 2007) in the past decade. Fungicides such as pyraclostrobin and propiconazole can control foliar diseases and enable many crops to achieve a high physiological benefit especially at late growing period, thus delaying leaf senescence and increasing yield (Blandino et al., 2012; Joshi et al., 2014; Testa et al., 2015). Previous studies showed that foliar fungicides "Cabrio®" (active ingredient: pyraclostrobin) and "Opera®" (active ingredient: pyraclostrobin + epoxiconazole) released by BASF can efficiently delay leaf senescence and increase yield of maize (You et al., 2012; Lazo and Ascencio, 2014; Zhang et al., 2014). The use of these fungicides might be a useful strategy to offset the adverse effects of climate change and environmental stress on the maize yield in the North China Plain.

Hypothetically, the adverse effects of climate change on maize yield can be offset by extending growing period but to only some extent because of the limited growing period of maize in the double cropping system in the North China Plain. Alongside the extended growing period, promoting leaf productivity is speculated to further offset the effects of climate change. The objectives of this study were (i) to detect the adverse effects of climate change on summer maize yield in the North China Plain in the past six decades, (ii) to reduce the adverse effects of climate change and environmental stress, and (iii) to find out possible strategies to further increase maize yield in this region.

2. Materials and methods

2.1. Experimental site and climate database

The field experiment was conducted in 2011–2015 at Wuqiao Experimental Station (37°41′02″N, 116°37′23″E) of China Agricultural University on a loam soil, located in the east of North China Plain. This region is in a warm temperature zone with a cold and dry winter and a hot and short summer. Mean annual temperature is 14.0 °C, mean annual precipitation is 550 mm with a large inter-year variation, and accumulated solar radiation is 4600–5800 MJ m^{-2} in the past six decades. Meteorological data from 1954 to 2015 for Wuqiao were obtained from the China Meteorological Data Sharing Service System (http://www.cdc.nmic.cn; Botou site). The downloaded climate data include daily solar radiation, precipitation, relative humidity of the air, wind speed, and daily mean, maximum and minimum temperature. Annual solar radiation and precipitation were the sum of daily solar radiation and precipitation, respectively. Growing degree days (GDD) per year was the sum of daily GDD. Daily GDD = (maximum temperature + minimum temperature)/2–10 °C, and daily GDD was not summed up when it was less than 0 °C.

The experiment was arranged in different experimental designs in different years, a split plot design with foliar fungicides as main factor and plant density or nitrogen as second factor in 2012–2015 (Table 1). Maize hybrid ZD958 that has been widely adopted in the North China Plain in the past decades was used. Foliar fungicides "Cabrio" in 2011–2014 and "Opera" in 2015 were sprayed at 9-leaf stage, respectively, in a concentration of 1.5 ml L^{-1}, corresponding to 500 ml fungicides ha^{-1}. The control treatment was to spray the same amount of H_2O at 9-leaf stage. Plant densities ranged from 67,500 to 90,000 plants ha^{-1}, differing between years (Table 1). At sowing, 60 kg N ha^{-1} was applied in all the experimental years 2011–2015, and an extra 60 kg N ha^{-1} was added at 6-leaf stage in the nitrogen treatment of 120 N ha^{-1} in 2011; in the treatment of 180 ha^{-1}, an extra 120 kg N ha^{-1} was applied at 6-leaf stage. Other fertilizers such as 105 kg P_2O_5 ha^{-1}, 120 kg K_2O ha^{-1}, and 15.0 kg $ZnSO_4$ ha^{-1} were applied together at sowing. The plot size was 6 × 10 m^2 with a row spacing of 0.6 m. Each treatment had at least three replicates. Irrigation was performed at any growth stage to avoid drought stress.

Maize seeds were sown into the standing wheat stubble immediately after harvest of winter wheat without any tillage, which was performed at the middle or late June. The fields were overplanted and thinned to

Table 1
Field experiment, experimental treatments (i.e. foliar fungicides, plant density, and nitrogen), and sowing and harvest time from 2011 to 2015.

Year	Foliar fungicides	Density[c] plant ha^{-1}	Nitrogen kg ha^{-1}	Sowing	Harvest
2011	Cabiro[a]	75,000 90,000	120; 180	24/06/2011	06/10/2011
2012	Cabiro[a]	67,500 90,000	180	15/06/2012	04/10/2012
2013 - 2014	Cabiro[a]	67,500 82,500[d]	180	15/06/2013 19/06/2014	01/10/2013 02/10/2014
2015	Opera[b]	90,000	180	10/06/2015	05/10/2015

[a] Foliar fungicides "Cabrio" at the level of 500 ml ha^{-1} was sprayed at 9-leaf stage.
[b] Foliar fungicides "Opera" at the level of 500 ml ha^{-1} was sprayed at 9-leaf stage.
[c] Density treatments were classified into two groups, low density treatment including 67,500 and 75,000 plants ha^{-1} and high density treatment including 82,500 and 90,000 plants ha^{-1}.
[d] Two plant densities 67,500 and 82,500 plants ha^{-1} were used in 2013, and only 82,500 plants ha^{-1} in 2014.

the expected plant density at around 3-leaf stage. Harvest was conducted at the early October. During the whole growing period, optimal management was used to control weeds, insects and diseases.

2.2. Experimental data

Green leaf area of three randomly sampled plants per plot was measured at silking, 25 days after silking (mid grain filling stage) and harvest using the formula: Green leaf area = leaf length × leaf width × 0.75. Leaf area index was expressed as the accumulated green leaf area per unit soil area. To describe the leaf senescence after silking, relative green leaf area index (RGLA) was simulated with a curvilinear equation:

$$y = ae^{b-cx}/(1 + e^{b-cx})$$

where y is RGLA, x the days after silking, a the initial RGLA (set to 1 in this study), b the scale parameter, and c the shape parameter. Parameters b and c were determined by LAI at silking, mid-grain filling and harvest stages (Liu et al., 2009; Chen et al., 2013).

After measuring green leaf area, the sampled plants were oven dried at 80 °C for 48 h, and were weighted to determine dry biomass at silking, mid grain filling and normal harvest stages. Kernel weight and grain filling rate were detected after silking on 5-day intervals in 2013 and 2014, and on weekly intervals in 2015; 100 grain kernels from top, central, and bottom positions of five ears per plot were sampled, dried, and weighted, respectively. Grain filling rate was calculated as kernel weight divided by grain filling period. Kernel weight and grain filling rate were expressed as the mean values across top, middle, and bottom kernel positions in the ear.

At harvest, ears were collected and counted in four adjacent rows 5 m long in each plot. Kernels per ear were counted, threshed and oven-dried at 80 °C to a constant weight. Six 1000-kernel samples were weighed to measure 1000-kernel weight. The grain yield was adjusted to 14% moisture content. Harvest index was expressed as the proportion of dry grain weight over dry biomass per area.

2.3. Hybrid-maize model and parameters

The Hybrid-Maize Model combined crop growth and development model in CERES-Maize (Kiniry et al., 1992) and mechanistic formulas of photosynthesis and respiration in INTERCOM (Kropff and van Laar, 1993) and WOFOST (Van Diepen et al., 1989). This model has specific features such as integration of GDD, gross assimilation, and growth or maintenance respiration (Yang et al., 2004). GDD is defined as the sum of daily average temperature over 10 °C during maize growing season. The Hybrid-Maize model simulation on maize grain yield was widely accepted, and the accuracy was reliable at different regions (Yang et al., 2004 2006; Chen et al., 2013). The input parameters comprise of general parameters (i.e. historical weather data, sowing date, variety maturity, and plant density), water condition (rained or irrigated), and soil properties. The key parameters for crop management, crop growth, respiration and photosynthesis, and soil are allowed to be modified based on field records and observations.

In the present study, soil parameters were default values in the model. Weather variables consist of solar radiation, daily air maximum and minimum temperature, relative humidity, rainfall, and reference evapotranspiration. The crop parameters were adjusted based on field observation in 2012 (Table 2). GDD, solar radiation, and precipitation in 2012 at the experimental site were 2634.7 °C, 5463.3 MJ m^{-2}, and 675 mm, respectively. Irrigation was conducted when drought stress occurred during maize growing season, so estimate irrigation of water requirement was selected in the simulation. Sowing date was set on June 15 with a sowing depth of 4 cm.

Table 2
Crop parameters of maize hybrid ZD958 at the plant density of 67,500 plant ha^{-1}, based on the field observation in 2012; these parameters were used as inputs for Hybrid-Maize Model.

Item		Non-fungicides	Fungicides
Density (plant ha^{-1})		67,500	67,500
Potential kernel number $plant^{-1}$		590	600
Potential grain-filling (mg $kernel^{-1}$ d^{-1})		7.93	8.50
Dry matter translocation efficiency (g g^{-1})		0.38	0.42
Relative leaf area index at maturity (m^2 m^{-2})		0.66	0.73
Total DDG (°C)		1645	1632
Pre-silking DDG (°C)		960	950
Phenology (date, month/day)	Sowing	06/15	06/15
	Silking	08/09	08/10
	Harvest	10/04	10/04

Growing degree days GDD = (maximum temperature + minimum temperature)/2-10 °C.

2.4. Statistical analysis

The analysis of variance in dry biomass and LAI and regression between observed yield and LAI was performed using SPSS Statistics 17.0. The difference was compared using the least significant difference test (LSD). Regression analysis was used to describe the linear trend of climate change (i.e. temperature, solar and precipitation), growing period, and simulated yield of maize. Based on the objectives of the present study, the most important and relevant experimental data were pooled out from the experimental results. Effects of"Cabrio" and "Opera" were averaged over years, which was referred to as "Fungicides". The treatment of spraying water was referred to "Water". Density treatments were classified into two groups, low density treatment including 67,500 and 75,000 plants ha^{-1} and high density treatment including 82,500 and 90,000 plants ha^{-1}. Interaction effects of foliar fungicides and nitrogen was detected based on the experimental results in 2011.

3. Results

3.1. Climate change from 1954 to 2015

In the past six decades, annual GDD, as indicative of the total thermal time, significantly increased at a rate of 4.4 °C yr^{-1} (Fig. 1a). In contrast, annual solar radiation and precipitation decreased at the rate of 12.93 MJ m^{-2} yr^{-1} and 1.95 mm yr^{-1}, respectively (Fig. 1bc). A large variation in precipitation between years were detected, and the variation became smaller over time.

3.2. Simulated growing period and yield of maize

The Hybrid maize model was used to simulate the growing period and grain yield of maize, based on the observations in 2012. Vegetative growing period (pre-silking, vDays) and reproductive growing period (post-silking, rDays) can be automatically calculated by the model. In the past six decades, the simulated vDays, rDays and tDays significantly decreased (Fig. 2). The decrease in rDays was much faster than that in vDays, i.e. 0.144 *vs.* 0.048 day yr^{-1} (Fig. 2). The simulated yield also decreased significantly with climate change in the past decades (Fig. 3).

In one simulation scenario, the growing degree days (GDD) was set to a specific value (1632 °C, Table 2), and sowing date was set on different dates from June 1 to July 10 on 5-day intervals. The proportion of reproductive growing period over total growing period (rDay/tDay) steadily increased with the delayed sowing time, and reached to the highest level on the sowing date of June 30, followed by a decline (Fig. 4A). The simulated yield had the same pattern with the trend in the proportion of rDays/tDays as sowing date was delayed (Fig. 4B).

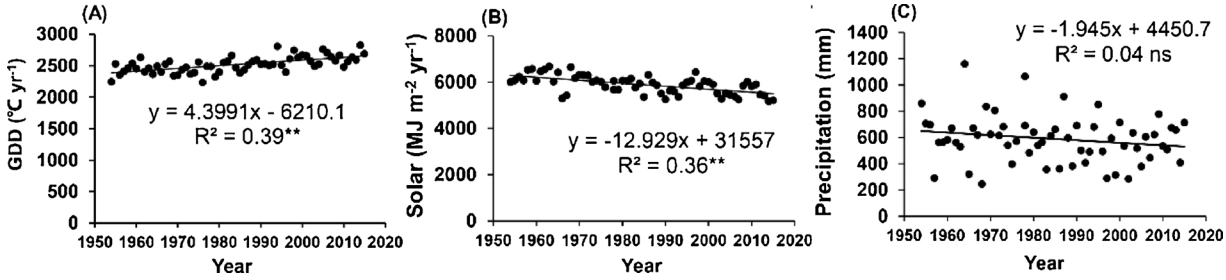

Fig. 1. Growing degree days (GDD), solar radiation and precipitation per year from 1954 to 2015 at the experimental site. ** indicate significance at $P < 0.001$; ns, not significant at $P < 0.05$.

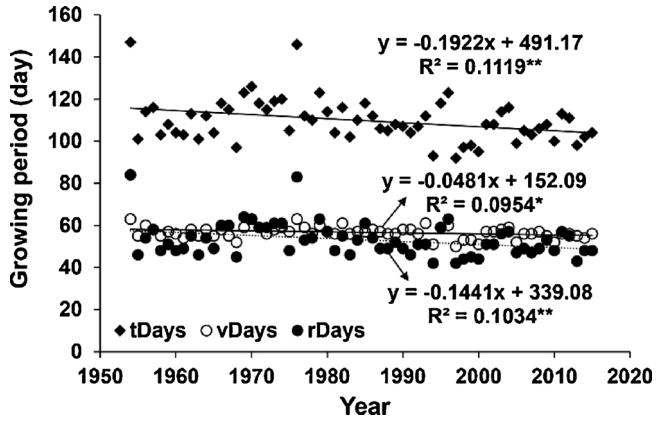

Fig. 2. Simulated growing days of maize in vegetative growth period (vDays), reproductive growth period (rDays), and total growth period (tDays) as effect of climatic change in the past six decades from 1954 to 2015; *,** indicate significance at $P < 0.05$ and < 0.01, respectively.

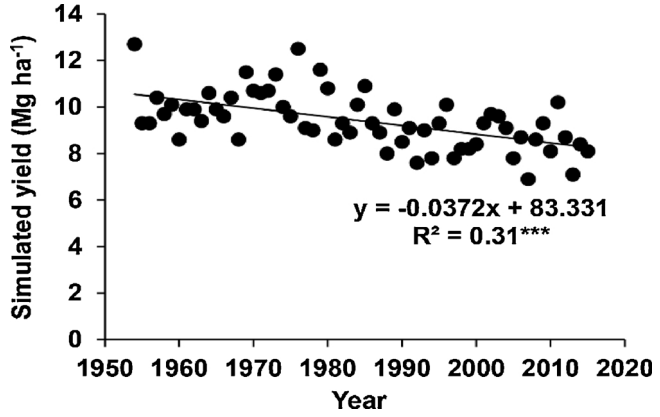

Fig. 3. Simulated yield trend of summer maize as effect of climate change in the past six decades from 1954 to 2015; *** indicates significance at $P < 0.001$; sowing date was set on June 15. Simulation was based on the observations in 2012.

3.3. Leaf area dynamics

On average, the overall mean leaf area index (LAI) was larger in the treatment of "Fungicides" than in the treatment of "Water", and the difference became significant at maturity stage (Fig. 5A). The difference became more obvious at high plant density (Fig. 5B) and at low nitrogen level (Fig. 5C). Particularly, LAI in the treatment of N120 + fungicides was significantly larger than that of N180 + water.

Plant density had significant effects on LAI at silking stage, but not at maturity (Fig. 5B). There was no significant difference in LAI detected between treatments of N120 and N180 at both silking and maturity stages, irrespective of foliar fungicides effects (Fig. 5C).

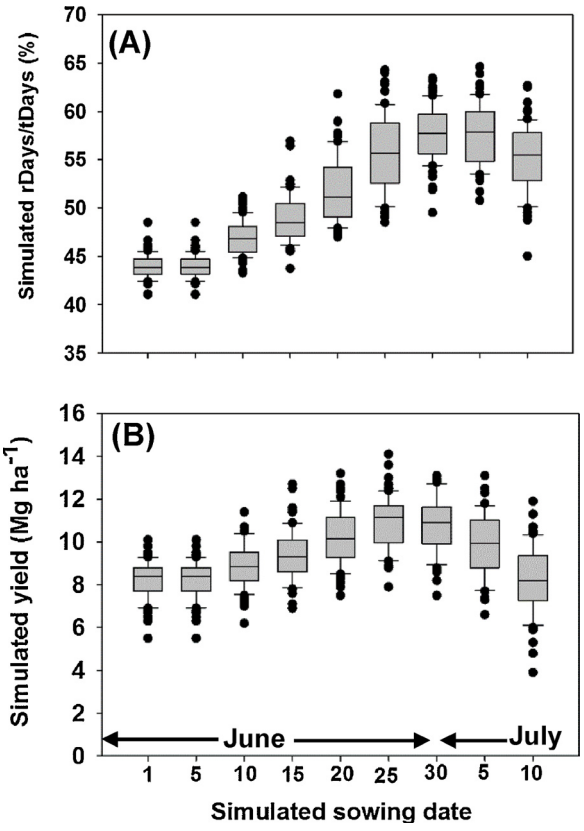

Fig. 4. Simulated proportion of reproductive growing period over total growing period (A, rDays/tDays) and simulated yield (B) of summer maize as effect of changes in sowing time in the past six decades from 1954 to 2015. Simulation was based on the field observations in 2012.

The relative green leaf area (RGLA, representative of leaf senescence) of treatment "Fungicides" became increasingly larger than that of "Water", especially after approximately 20 days after silking (Fig. 6A). Regardless of foliar fungicides, high plant density resulted in a faster leaf senescence than low plant density during the entire grain filling period (Fig. 6B). Treatments "N180″ had very close RGLA with "N120″, but had an increasingly larger RGLA than"N120″(Fig. 6C). Treatment of"N120 + fungicides" had an larger RGLA than treatment of"N180 + water" especially in the late growth period.

At normal harvest time, 60% of leaves stayed green in the treatment of "Fungicides", corresponding to a LAI value of 2.5–3.0, depending on plant density and nitrogen level. RGLA declined to 20–40% in the treatment "Water" at normal harvest, corresponding to a LAI value of 1.5–2.0.

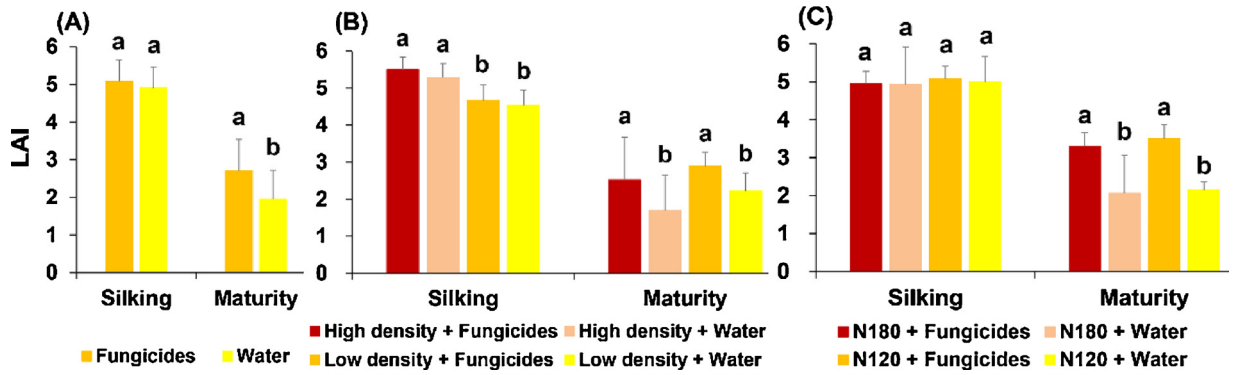

Fig. 5. Leaf area index (LAI) at silking and maturity stage as effect of foliar fungicides (A, mean LAI across year, plant density and nitrogen treatment), interaction of plant density and foliar fungicides (B, mean LAI across year and nitrogen), and interaction of foliar fungicides and nitrogen (C, mean LAI across plant density in 2011). Foliar fungicides were sprayed at 9-leaf stage, and the same amount of water was sprayed as control treatment. Values with the same letter at the same growth stage are not significantly different; bars indicate standard error of mean.

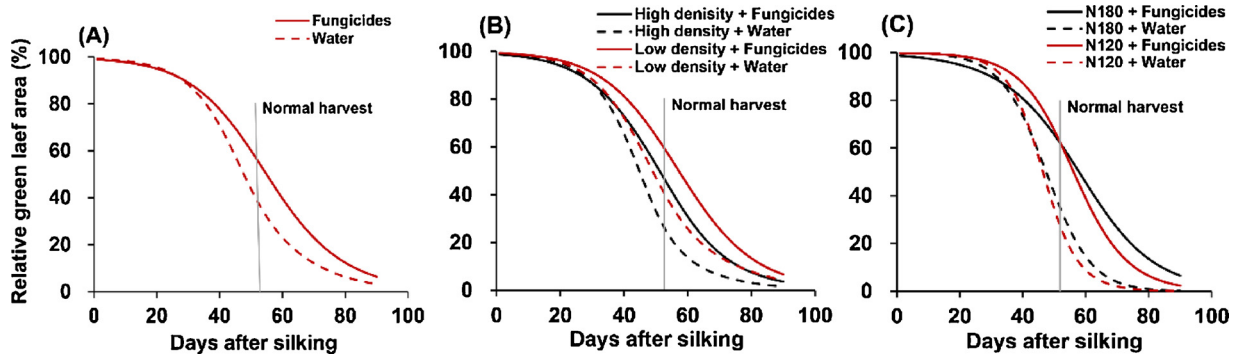

Fig. 6. Changes of relative green leaf area (RGLA) over time post-silking as effect of foliar fungicides (A, mean RGLA across year, plant density and nitrogen treatment), interaction of plant density and foliar fungicides (B, mean RGLA across year and nitrogen), and interaction of foliar fungicides and nitrogen (C, mean RGLA across plant density in 2011). RGLA was simulated with curvilinear equation $y = aeb–cx/(1 + eb–cx)$ where y is RGLA, x days after silking, a the initial RGLA (set to 1 in this study), b the scale parameter, and c the shape parameter (Liu et al., 2009); b and c were calculated based on measured LAI at silking, mid grain filling and harvest stages. Foliar fungicides were sprayed at 9-leaf stage, and the same amount of water was sprayed as control treatment (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3.4. Dry biomass and grain filling

On average, dry biomass between treatments of "Fungicides" and "Water" were very close at mid grain filling stage (185.4 vs. 181.4 g plant^{-1}), but treatment of "Fungicides" accumulated significantly larger dry biomass than "Water" during the period from mid grain filling to harvest (Fig. 7A). At high plant density, population dry biomass of "Fungicides" was significantly larger than that of "Water" in the period from mid grain filling to harvest (Fig. 7B). In both N180 and N120 levels, "Fungicides" significantly increased dry biomass than "Water" (Fig. 7C).

Kernel dry weight steadily increased after silking, and slowed down

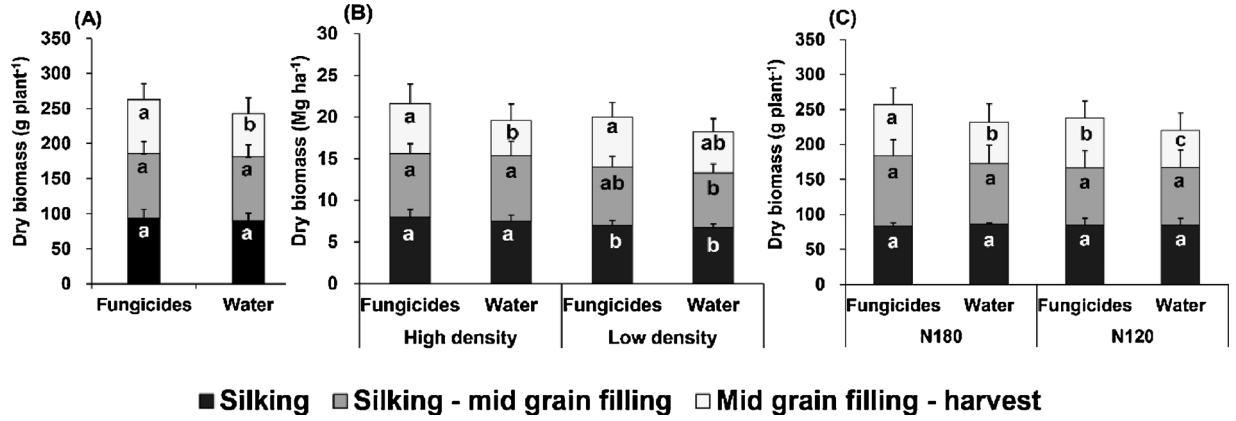

Fig. 7. Dry biomass accumulation pre-silking, from silking to mid grain filling (25–30 days after silking), and from mid grain filling to harvest as effect of foliar fungicides (A, mean value across year, plant density and nitrogen treatment), interaction of plant density and foliar fungicides (B, mean value across year and nitrogen), and interaction of foliar fungicides and nitrogen (C, mean value across plant density in 2011). Foliar fungicides were sprayed at 9-leaf stage, and the same amount of water was sprayed as control treatment. Values with the same letter in the same growing period are not significantly different; bars indicate standard error of mean.

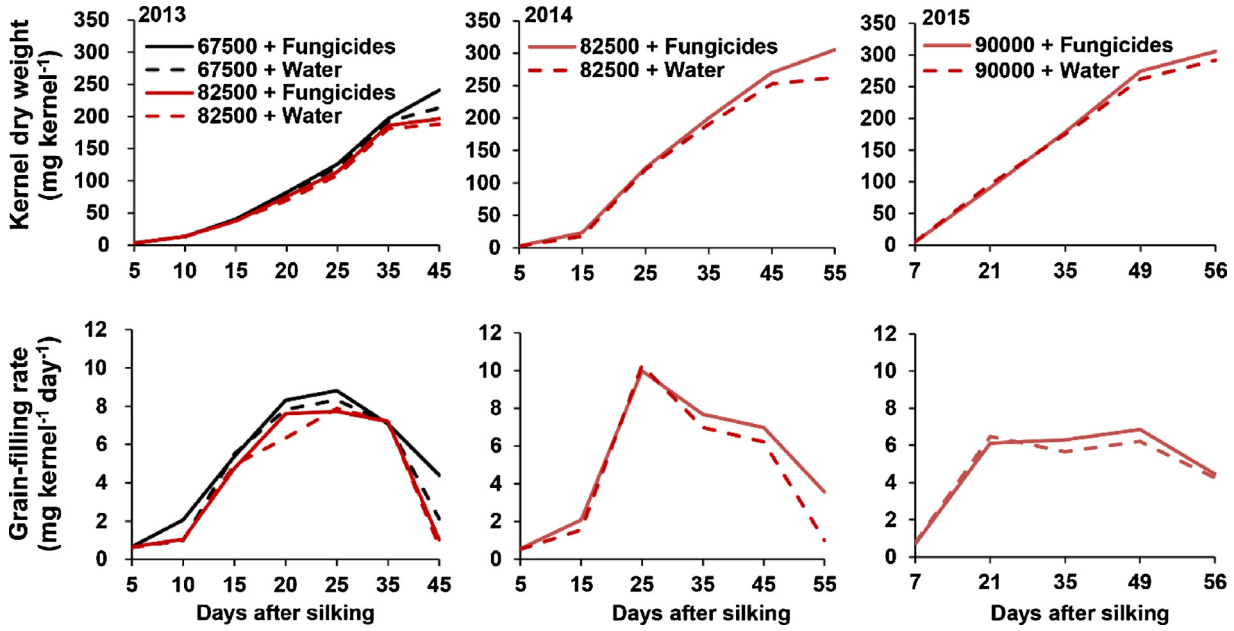

Fig. 8. Changes of kernel dry weight and grain filling rate over time during the period post-silking as effect of plant density and foliar fungicides in 2013, 2014 and 2015. Values of 67,500, 82,500 and 90,000 indicate plant densities; foliar fungicides were sprayed at 9-leaf stage, and the same amount of water was sprayed as control treatment.

at 35–45 days after silking, depending on year and plant density (Fig. 8A). Compared to treatment "Water", "fungicides" enable kernel dry weight to maintain a faster increase during late growing period, resulting in an increasingly larger kernel dry weight.

Correspondingly, grain filling rate kept increasing from approximately 0.5 mg kernel^{-1} day^{-1} at about one week after silking, and reached the highest level of 8.0 mg kernel^{-1} day^{-1} at around 25 days after silking (Fig. 8B). Afterwards, the grain filling rate declined especially for the treatment of "Water". The grain filling rate at the treatment "Fungicides" became increasingly larger in the late growing period than that in the treatment "Water".

3.5. Yield, components, and harvest index

The overall mean yield was slightly higher (9.5 *vs.* 9.4 Mg ha^{-1}) in the treatment "Fungicides" than that in treatment "water", because of the increased kernel number ear^{-1} and increased TKW (Table 3). On the contrary, harvest index (HI) was much smaller (46.2 *vs.* 49.5%) in "Fungicides" than that in "Water", which was also observed in the treatments of density and nitrogen. Particularly, the yield difference between treatments "Fungicides" and "Water" became 0.2 Mg ha^{-1} at high plant density, and 0.6 Mg ha^{-1} at the treatment of N120.

3.6. Yield and leaf dynamics

Quadratic equations were fit to the relationships between yield, LAI at silking ($LAI_{(silking)}$), LAI decrease from silking to maturity ($LAI_{\triangle(silking - maturity)}$), and speed of LAI decrease from silking to maturity ($LAI_{\triangle(silking - maturity)}$/day, Fig. 9). Yield reached the highest level when $LAI_{\triangle(silking - maturity)}$ was about 3 or $LAI_{\triangle(silking - maturity)}$/day was about 0.05 day^{-1}.

3.7. Yield decrease by climate change and possible adaption methods

Simulated maize yield decreased by 2.3 Mg ha^{-1} from 1954 to 2015 (Climate, Fig. 10). In another simulation scenario, sowing date was set

Table 3
Observed yield, yield components (kernel number ear^{-1}; 1000-kernel weight, TKW) and harvest index (HI) of summer maize as effect of foliar fungicides, interaction of foliar fungicides and plant density, and interaction of foliar fungicides and nitrogen. Values with the same letter are not significantly different, comparison between "Fungicides" and "Water" in each item only. Values in the bracket mean standard error of mean.

		Grain yield (Mg ha^{-1})	Kernel ear^{-1}	TKW (g)	HI (%)
Overall mean[a]	Fungicides	9.5a (*1.3*)	462.1a (*56.4*)	314.5a (*39.6*)	46.2a (*7.0*)
	Water	9.4a (*1.2*)	456.3a (*47.4*)	309.7a (*34.5*)	49.5a (*7.3*)
High density [b]	Fungicides	9.2a (*1.0*)	433.2a (*53.7*)	315.2a (*40.3*)	43.4a (*2.4*)
	Water	9.0b (*0.7*)	424.1a (*30.9*)	307.9b (*33.1*)	46.2a (*4.3*)
Low density [c]	Fungicides	9.7a (*1.6*)	491.0a (*46.7*)	313.8a (*43.6*)	49.1a (*9.1*)
	Water	9.7a (*1.5*)	488.4a (*39.0*)	311.5a (*39.6*)	52.9a (*8.5*)
N180 [d]	Fungicides	9.1a (*0.1*)	421.4a (*47.6*)	283.0a (*7.9*)	45.4b (*1.3*)
	Water	9.2a (*0.1*)	427.6a (*45.2*)	284.3a (*3.2*)	52.3a (*2.8*)
N120 [d]	Fungicides	9.4a (*0.9*)	432.0a (*60.6*)	284.0a (*4.8*)	43.3a (*7.4*)
	Water	8.8b (*0.1*)	422.2b (*47.6*)	276.1b (*7.9*)	48.9a (*1.3*)

[a] Mean value across year, plant density and nitrogen treatment.
[b] Mean value across year and nitrogen at 82,500 and 90,000 plants ha^{-1}.
[c] Mean value across year and nitrogen at 45,000 and 75,000 plants ha^{-1}.
[d] Mean value across plant density in 2011.

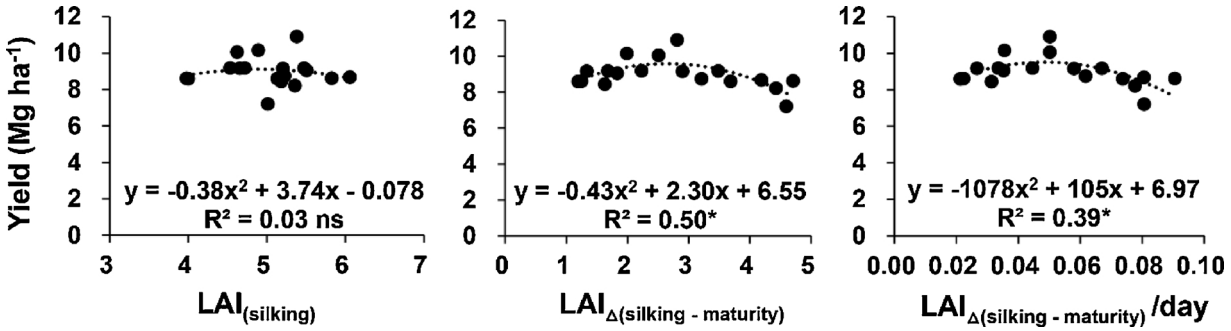
Yield (Mg ha-1)
y = -0.38x² + 3.74x - 0.078
R² = 0.03 ns
LAI(silking)
y = -0.43x² + 2.30x + 6.55
R² = 0.50*
LAIΔ(silking - maturity)
y = -1078x² + 105x + 6.97
R² = 0.39*
LAIΔ(silking - maturity) /day

Fig. 9. Observed yields plot against leaf area index at silking stage ($LAI_{(silking)}$), LAI decrease from silking to maturity ($LAI_{\triangle(silking\ -\ maturity)}$), and decrease speed of LAI from silking to maturity ($LAI_{\triangle(silking\ -\ maturity)}$ /day) in summer maize; values were collected from field experiments during 2011 – 2015. * significant at $P < 0.05$; ns, not significant; dashed line indicates yield trend with changes of $LAI_{(silking)}$, $LAI_{\triangle(silking\ -\ maturity)}$ and $LAI_{\triangle(silking\ -\ maturity)}$ /day.

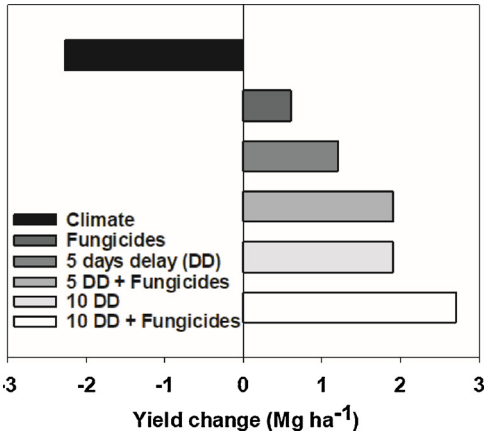

Fig. 10. Simulated yield change of maize relative to the yield at normal harvest. Climate indicates yield reduction as a result of climate change from 1954 to 2015; Fungicides, fungicide effect on increasing maize yield; 5 DD or 10 DD, effects of 5 or 10 days delayed harvest on increasing maize yield, 5 DD or 10 DD + Fungicides, effects of combined fungicides and five or 10 days delayed harvest on increasing maize yield. Simulation was based on the observations in 2012. Normal harvest was set on October 4.

on June 15, and harvest was delayed by 5 and 10 days after normal harvest. Compared to normal harvest, the simulated yield increased by 1.2 and 1.9 Mg ha^{-1} in 5-day (5 DD) and 10-day delayed harvest (10 DD), respectively. Fungicides alone increased maize yield by 0.6 Mg ha^{-1} compared to the "water" treatment at normal harvest. By contrast, together with foliar fungicides, 5 DD and 10DD harvest could increase yield by 1.9 and 2.7 Mg ha^{-1} (Fig. 10).

4. Discussion

4.1. Climate change

Similar to climate change around the world (Butler and Huybers, 2013; Chen et al., 2013; Lobell et al., 2011; Olesen et al., 2011), a significant warming trend was observed in the North China Plain from 1954 to 2015 (Fig. 1). Also, the significantly decreased trend of annual solar radiation at the present study was consistent with findings of Wang et al. (2012), or with the reduced annual sun shine hours from 1980 to 2005 in the study of Liu et al. (2010). There was no consistent trend in annual precipitation between studies conducted at the North China Plain, but the trend was not significant in all the studies (Liu et al., 2010; Wang et al., 2012; Zhang et al., 2015a, 2015b). It was further confirmed that climate change had negative impacts on maize yield, which can be attributed to the reduced growing period (Fig. 2) (Estrella et al., 2007; Tao et al., 2014; Xiao et al., 2016). During the shortened growing period, solar radiation accumulation decreased, resulting in a further decrease in yield. Compared to vegetative growing period, reproductive growing period was reduced to a greater extent by the warming climate (Fig. 2), which more likely accounted for the reduced yield (Hedhly et al., 2009; Xiao et al., 2016).

4.2. Foliar fungicides

Foliar fungicides used at the present study delayed leaf senescence (Fig. 5 and 6) and increased dry matter accumulation (Fig. 7), thus leading to an increase in yield by up to 6.8% (Table 3). These results corroborated previous findings of Blandino et al. (2012) and Zhang et al. (2014). Based on the close values between treatments of "Fungicides" and "Water" in kernel weight, grain filling rate, and dry matter accumulation before mid grain filling, effects of "Fungicides" occurred mainly in the late grain filling period. Compared to the first half grain filling period, the second half is less contributable to the final yield of maize (Rajcan and Tollenaar, 1999), which can explain the unexpected yields in the treatment of "Fungicides". First, leaf senescence accelerated at late grain filling period (Fig. 6), resulting in a rapid reduction in biomass productivity. Particularly second, a significantly larger dry biomass was accumulated at late grain filling period in the treatment of "Fungicides", but they cannot be effectively transported into the grains due to the early harvest, leading to a lower harvest index (Table 3). Compared to the delayed leaf senescence, increasing leaf productivity especially from silking to mid grain filling is supposed to be more important for the further increase in maize yield in the cropping system winter wheat – summer maize.

At high plant densities and low nitrogen application, effects of "Fungicides" on maintenance of green leaf area, dry biomass productivity, and yield were apparently more effective than at low densities and low nitrogen level. This suggested that foliar fungicides have a greater implication at environmental stress or resource limited conditions. In the context of food security and green agriculture around the world (Godfray et al., 2010; Koohafkan et al., 2012)., Increasing plant density to increase yield as well as reducing nitrogen application to reduce environmental burden are being widely considered. This study, taking both high plant density and low nitrogen into account, probably provided an alternative method to cope with the conflict between crop yield and environments.

4.3. Leaf area dynamics and yield of maize

Optimum grain yield of maize could be achieved at the optimal LAI (Bavec and Bavec, 2002). In the present study, the optimal LAI ranged from around 4.5 to 5.5, smaller than the values of 6–7 at other regions (Van Roekel and Coulter, 2012), probably due to different varieties and environmental conditions. Afterwards, yield decreased with increase in LAI, indicating that it is difficult to further improve maize yield by increasing plant densities at the experimental site, at least with variety

"ZD958". Maize varieties with much compacter plant type that can adapt to high plant population are likely to increase yield in this region (Huang et al., 2017; Liu et al., 2017).

Several studies reported that stay-green varieties can produce more yields in maize (Zheng et al., 2009; Chen et al., 2013; Antonietta et al., 2014), which however was not observed in the present study (Fig. 9). Similarly, the stay-green maize cultivar used in the study of Acciaresi et al. (2014) and Antonietta et al. (2014) failed to produce expected grain yield, especially at high plant densities. In addition to the insufficient biomass transportation, the lower yield at the small LAI reduction from silking stage to maturity ($LAI_{\triangle(silking - maturity)}$) was probably attributed to the slow leaf senescence at lower canopy layers. These green leaves at lower canopy layer could become biomass sink rather than source at late growing period because of the high respiration (Antonietta et al., 2014). Spontaneous leaf senescence at lower canopy layer is supposed to be an energy-saving strategy for the whole plant (Schippers et al., 2015). In contrast, the smaller yield at the large range of $LAI_{\triangle(silking - maturity)}$ probably resulted from the fast leaf senescence at the whole plant level. The relationship between leaf productivity and leaf area dynamics over time at this region should be further studied in the future research.

4.4. Possible strategies to further increase summer maize yield in the North China Plain

According to the simulated results on the relationship between yield and harvest date, further increase in maize yield could be realized by using foliar fungicides and late harvest (Fig. 10). Delaying maize harvest by 5 or 10 days could offset over 50 or 80% of climate change effects in the past six decades in the North China Plain. Delayed harvest 10 days later than normal harvest can be performed at early or middle October, by then the maximum temperature was over 20 °C and minimum temperature over 10 °C (Supplementary Fig. 1). This condition will not lead to cold stress for maize grain filling (Sánchez et al., 2014). Spraying fungicide offset around 25% of the climate change effects. Together with foliar fungicides, 10-day delayed harvest completely offset the negative effects of climate change. These results clearly indicate that either extending growing period or promoting leaf productivity alone is limited to offset climate change effects on maize yield in the cropping system of winter wheat – summer maize in the North China Plain. When they act together, the climate change effects on maize yield can be completely offset in the past six decades.

Progressive climate change, environmental stress, and unsuitable farming practice (e.g. too early harvest) will continuously increase the difficulty in increasing maize yield in the North China Plain. The reduced solar radiation in the short growing period of maize could further reduce yield. It is known that reproductive growing period as well as leaf productivity in the first half grain filling period contribute more to the yield increase of maize. Therefore, strategies that can increase proportion of reproductive growing period over the whole growing period (rDay/tDay) and increase leaf productivity after silking stage, should be considered, such as variety, timing of foliar fungicide application, and sowing date.

Furthermore, solar radiation in the first half grain filling period of maize is limited under the current sowing and harvest time in this region (Supplementary Fig. 2). Thus, reducing coincidence period of low solar radiation with the first half grain filling period becomes particularly important. In addition, maize plants could not reach physiological maturity before normal harvest under the current cropping system; more than 40% of leaves still stayed green at harvest (Fig. 6). In the "Double-Delay" cropping technology i.e. late sowing of wheat and late harvest of maize, grain yield of maize was significantly increased (Wang et al., 2012; Xiao and Tao, 2014). However, maize yield variation between years in the "double-delay" cropping technology was observed by Sun et al. (2007), who reported that late harvest after middle October in the North China Plain cannot further increase maize yield. Low temperature at late grain filling period probably restrained the yield increase (Supplementary Fig. 1; Ying et al., 2000). Using cold-resistant maize varieties is likely a strategy to further increase maize yield in the context of late harvest.

5. Conclusion

With the progressive climate change, maize yield would keep decreasing in the cropping system summer maize – winter wheat in the North China Plain without the contribution of variety and crop management improvement. Reduced reproductive growing period is an important factor reducing yield. Increasing leaf productivity at late grain filling period can significantly increase dry biomass, but cannot produce an expected yield increase. Early harvest of maize can hinder sufficient biomass transportation to grains, and resulted in a low harvest index. At early grain filling period, increasing leaf productivity, as well as delaying harvest would be suitable strategies to further increase yield of summer maize in this region. Agronomic adaptions in variety and farming practice (e.g. sowing and harvest time) have a possible potential to offset the negative effects of climate change and abiotic stress in the growing period of maize in the North China Plain.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2018.07.007.

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